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SB2 and eclipsing binaries with GAIA and RAVE

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Abstract. The expected performance of GAIA satellite on eclipsing binaries is reviewed on the basis of (a) combined Hipparcos and ground-based observations mimicking GAIA data harvest, and (b) accurate simulations using the latest instrument model. It is found that for a large majority of the 16 000 SB2 eclipsing binaries that GAIA will discover at magnitudes $V \leq 13$, the orbital solutions and physical parameters will be derived with formal accuracies better than 2%. For the same stars the GAIA parallax errors will be $\sim$5 *micro*-arcsec, i.e. an error of 0.5% at 1 kpc, which will allow iterative refine of the parameters and physics used in orbital modeling. The detectability of SB2 binaries by the already up and running spectral survey RAVE is discussed. It is found that all F-to-M SB2 binaries showing a velocity separation $\geq$35 km sec^{-1} and a luminosity ratio $\geq$0.5 will be recognized as such.

1. GAIA

GAIA is the ambitious flagship mission approved by ESA for a launch not later than 2012, and possibly already by Q2 of 2010. The mission is designed to obtain extremely precise astrometry (in the *micro*-arcsec regime), multi-band photometry and medium/high resolution spectroscopy for a large sample of stars. The goals call for astrometry and photometry (5 broad and 11 medium bands covering the optical range) to be complete over the whole sky to $V = 20$, and spectroscopy complete to $V = 17.5$. The spectroscopy is primarily meant to provide the radial velocities and thus the 6$^{\rm th}$ component in the phase-space to complement the other five provided by astrometry. Each star will be visited around a hundred times during the five year mission life-time, in a fashion similar to the highly successful *Hipparcos* scanning mode. The spectra, photometry and astrometry acquired at each transit *epoch* will be individually accessible. GAIA has three telescopes/fields of view, roughly equally spaced over a great circle on

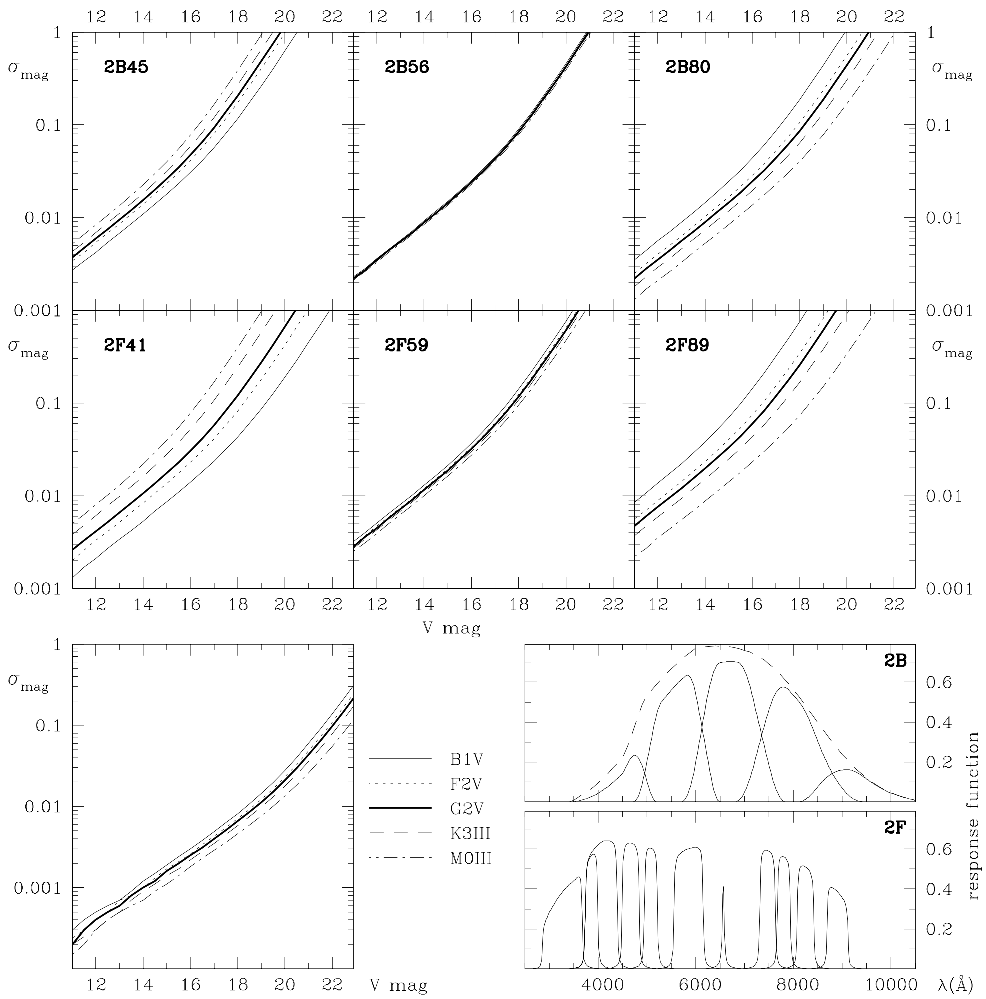

Figure 1. Errors of the magnitude measured over a single FOV transit for a sample of broad (upper raw), medium (middle raw) and white-light (lower left) GAIA photometric bands. The current set of broad and medium bands and the white-light photometric response of astrometric CCDs are depicted at lower right (from data courtesy of C.Jordi, on behalf of GAIA Photometric Working group).

the sky, so that every ∼2 hours along the 6 hours spin period, the same star will cross the field of view of Astro-1 (where astrometric position and magnitude in 5 broad bands are measured), of Astro-2 (identical to Astro-1), and of the Spectro-Photometric telescope (where spectra and photometry in ∼11 medium bands are collected).

Hipparcos performed photometry in three bands. H_P, a sort of white light covering the Johnson's B and V bands, has been the most accurate, with individual measurements accurate to 0.01 mag for solar type stars brighter than $V = 7.5$. The other two bands, V_T and B_T, were significantly less accurate.

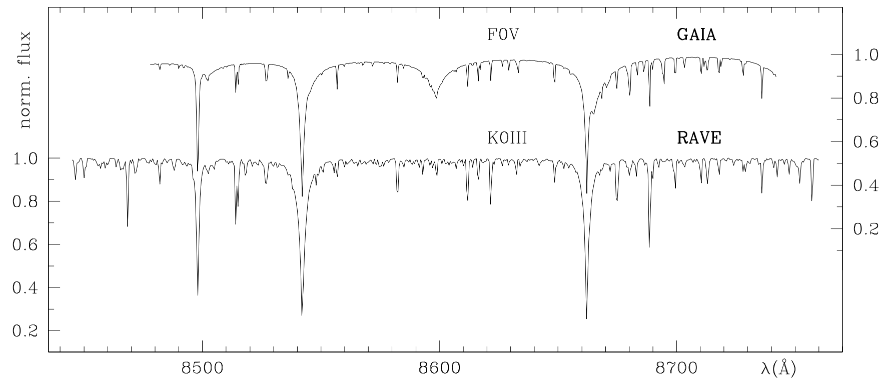

Figure 2. Comparison of GAIA (res. power 11 500) and RAVE (res. power 8 000) spectra for two sample stars.

GAIA will carry instead a fully featured photometric system, composed of a set of 5 broad and ∼11 medium bands, which are still under fine optimization. Figure 1 illustrates the expected errors on the magnitudes derived at each passage in the GAIA fields of view for three sample broad bands, three sample medium bands and for the photometric reading accompanying the *white light* astrometric measurement. Each epoch measurement in any band and for any star brighter than $V = 12$ (irrespective of the spectral type) will be accurate to better than 0.01 mag. In some bands (like in 2B56 or 2F59) the same limit is reached at $V = 14$. In white light, all individual measurements of stars brighter than $V = 18.5$ will be more accurate than 0.01 mag.

Field stars have colors corresponding to ∼G0 at $V = 10$, ∼K0 at $V = 15$ and cooler spectral types at fainter magnitudes. Therefore, optimization of spectroscopic observations has to be performed for G-K stars. Low metallicity stars of the Halo that covers a large fraction of the sky should be properly observed as well. Wavelength region satisfying these constraints is that of the CaII triplet in the far red (cf. Figure 2). This spectral region is interesting even for hotter stars, because it includes the head of the Paschen series and strong multiplets #1 and 8 of NI (for a detailed discussion see Munari 1999, 2002).

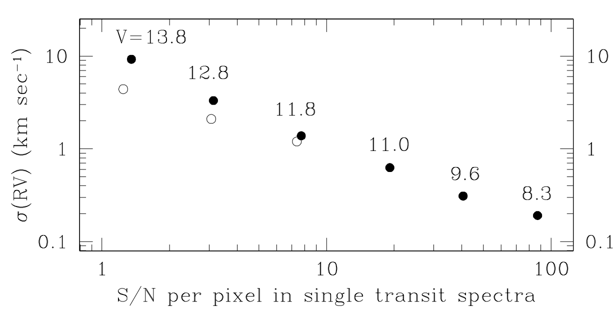

Figure 3. Errors of the GAIA radial velocities for single transit of single G-K stars (dots from Munari et al. 2003, circles from Katz et al. 2004, to be submitted).

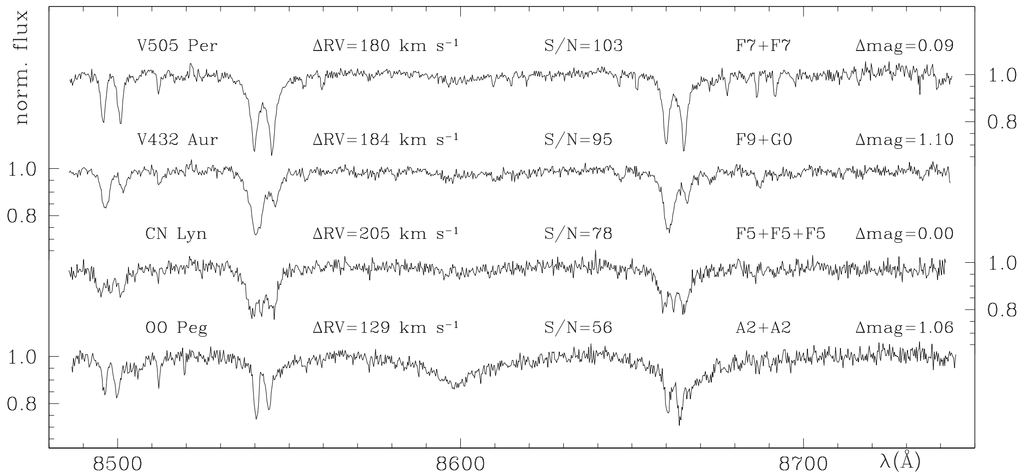

Figure 4. Examples of GAIA-like ground-based spectra of SB2 eclipsing binaries, where Δmag is the I_C mag difference of the two components (from Munari et al. 2001, Zwitter et al. 2003, Marrese et al. 2004). Note the resolved triple system CN Lyn.

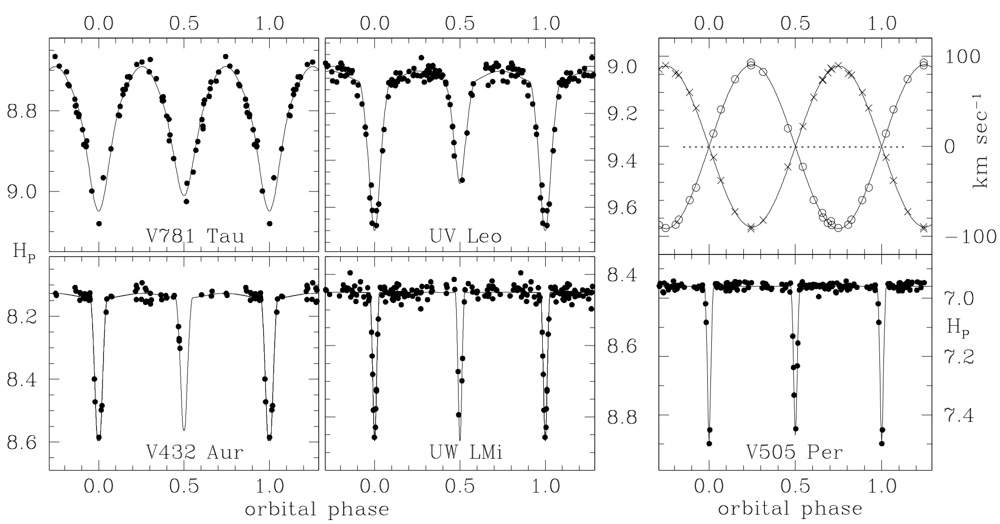

Figure 5. Hipparcos H_P lightcurves of SB2 eclipsing binaries for a range of eclipse phase width and number of points. The orbital solutions obtained in combination with radial velocities from ground-based GAIA-like spectroscopic observations are over-plotted (from Munari et al. 2001, Zwitter et al. 2003, Marrese et al. 2004).

Figure 3 illustrates the expected errors of GAIA radial velocities for single field stars of G-K spectral types and for a single transit. All stars brighter than $V = 14$ will have epoch radial velocities accurate to 10 km sec^{-1} or better, all those brighter than $V = 11.6$ to 1 km sec^{-1} or better.

$\boxed{M_1 + M_2 = 1.4\ M_\odot,\ [\mathrm{Fe/H}]{=}0.0,\ \text{on MS}}$

						$a = 11.9\ R_\odot$, $P = 4.02$ d, ΔV=30		$a = 296\ R_\odot$, $P = 503$ d, ΔV=150	
q=$\frac{M_2}{M_1}$	M_1 ($M_\odot$)	M_2 ($M_\odot$)	T_1 (K)	T_2 (K)	$l = \frac{L_2}{L_1}$	V^1_{rot} (km sec^{-1})	V^2_{rot}	V^1_{rot} (km sec^{-1})	V^2_{rot}
0.5	0.93	0.47	5720	3700	0.07	12.4	7.9	0.10	0.06
0.7	0.82	0.58	5290	4225	0.26	11.5	9.1	0.09	0.07
0.9	0.74	0.66	4930	4610	0.67	10.7	10.0	0.09	0.08
1.0	0.70	0.70	4775	4775	1.00	10.3	10.3	0.08	0.08

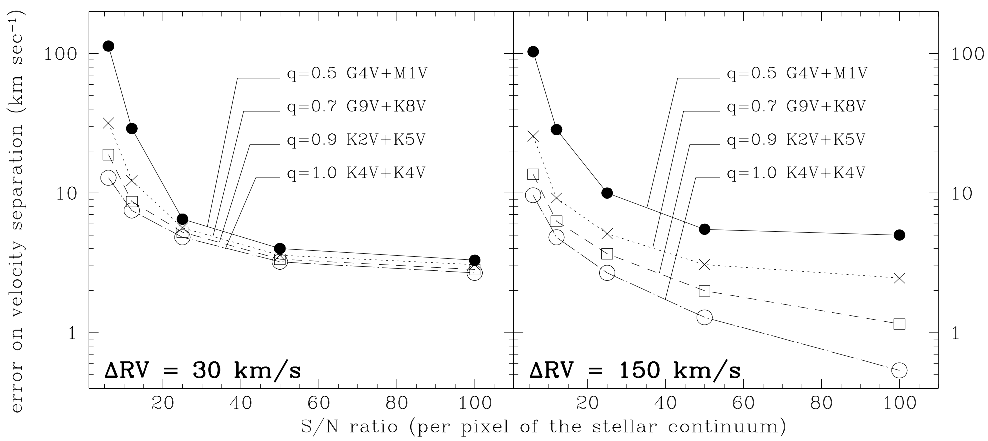

Figure 6. Results of Monte Carlo simulations to estimate the accuracy of GAIA radial velocity measurements of SB2 binaries observed at maximum velocity separation (orbital phases 0.25 or 0.75). Synthetic spectra of binaries with a total mass of 1.4 M$_\odot$, solar metallicity and both components on the Main Sequence were generated for the four given mass ratios. The latter fix individual masses, temperatures, spectral types and luminosity ratios. Two different orbital separations are assumed, so that eclipsing systems have velocity separations of 30 and 150 km sec^{-1} at quadrature (this fixes the synchronized rotational velocities). Synthetic stellar spectra used as input were calculated from Kurucz models using the R = 11 500 GAIA resolving power. Radial velocity measurements were made with an IRAF implementation of TODCOR routines. 30 and 150 km sec^{-1} corresponds to a separation of 2.3 and 11.5 pixels in the focal plane of the GAIA spectrograph, respectively. The simulations were performed for S/N=6, 12, 25, 50, 100 per pixel of the spectral continuum. The curves indicate the 2σ error loci (i.e. 66% of the trials gave errors smaller than indicated). A Δrad.vel.=30 km sec^{-1}=2.3 pixels corresponds to the Rayleigh resolution criterion for intrinsically sharp lines, and the accuracies displayed in the left panel go as expected with S/N and source brightness contrast. The Δrad.vel.=150 km sec^{-1}=11.3 pixels on the right panel corresponds instead to the situation where the radial velocity displacement is large enough to cause overlaps of unrelated spectral lines of the two components. In this case the luminosity ratio is the dominant factor governing the accuracy of the radial velocity measurements.

2. GAIA and the eclipsing binaries

Previous reviews of SB2 eclipsing binaries as seen by GAIA that nicely complement the present one have been given by Zwitter (2002, 2003), Zwitter & Munari (2004) and Milone (2003).

Minimal velocity separation for a firm recovery of the SB2 nature for solar type stars is of the order of 25-30 km sec^{-1}. Scaling Figure 3 to binary star case we see that radial velocity of each star in an SB2 binary with $V \leq 13$ and $L_2/L_1 \geq 0.5$ will be derived with an error not exceeding 10 km sec^{-1}. With $\sim$100 spectra per star randomly distributed in phase it may be expected that 1/3 of them will contribute to precise definition of semi-amplitudes K_1, K_2. If their accuracy is better than 10 km sec^{-1}, the resulting K_1 and K_2 will be accurate to 1 km sec^{-1} or better. Figure 1 shows that at $V = 13$ the epoch photometry in any of the 5+11 bands is accurate to 0.01 mag and in white light to an amazing 0.0006 mag for any of the considered stellar types. Therefore *all SB2 eclipsing binaries with* $V \leq 13$ *will be accurately observed by GAIA.*

It is important to check if GAIA will collect enough photometric observations to properly constrain the shape of the light-curve, and of the eclipse phases in particular. The measurements in white light and broad bands are essentially simultaneous and altogether $\sim$100 observations scattered over the five year mission lifetime will be collected (the exact number depends on the ecliptic coordinates and is generally comprised between 60 and 200). GAIA will also collect $\sim$ 170 measurements in the medium bands (again nearly simultaneous in all bands). Moreover, RVS sky mapper measurements obtained just before spectroscopic observations will provide additional $\sim$100 photometric points in a further photometric band covering the 8480-8740 Å spectroscopic wavelength range. Therefore, combining the 2B80 broad band, the 2F89 medium band and the RVS sky mappers, an average of about 370 independent photometric measurements will be obtained at wavelengths close to the Cousins $I_{\rm C}$ band, and 270 measurements for all other bands.

Such a number of photometric points should suffice for most of the cases. We have embarked in a long term project to assess the accuracy of GAIA investigations of SB2 eclipsing binaries (Munari et al. 2001, Zwitter et al. 2003, Marrese et al. 2004, Milone et al. 2004 to be submitted). Twelve systems have been studied so far, combining ground-based radial velocities acquired in the GAIA wavelength range with Hipparcos H_P photometry (to mimic GAIA photometric mapping). Typical light (and radial velocity) curves are presented in Figure 5, where orbital solutions are over-plotted. Such H_P mapping is generally sufficient to constrain the radii to 2-6%, depending of the total number of points and the width of the eclipse phases. With GAIA providing 3– to 4–times more points, the fraction of SB2 eclipsing binary systems for which the orbital solution will have formal errors in the 1-2% range should be remarkable. Similar conclusions were reached by Niarchos and Manimanis (2003) from their investigation in a GAIA-like mode of four over-contact systems.

Hipparcos derived a frequency of 0.8% of eclipsing binaries among the stars it surveyed. Applying this to star counts in the Galaxy, we may estimate that GAIA will discover 64 000 eclipsing binaries with $V \leq 13$. Applying Carquillat et al. (1982) conclusion that 1/4 of EBs are SB2, we end up with about 16 000 SB2 eclipsing binaries brighter than $V = 13$ for which GAIA should provide

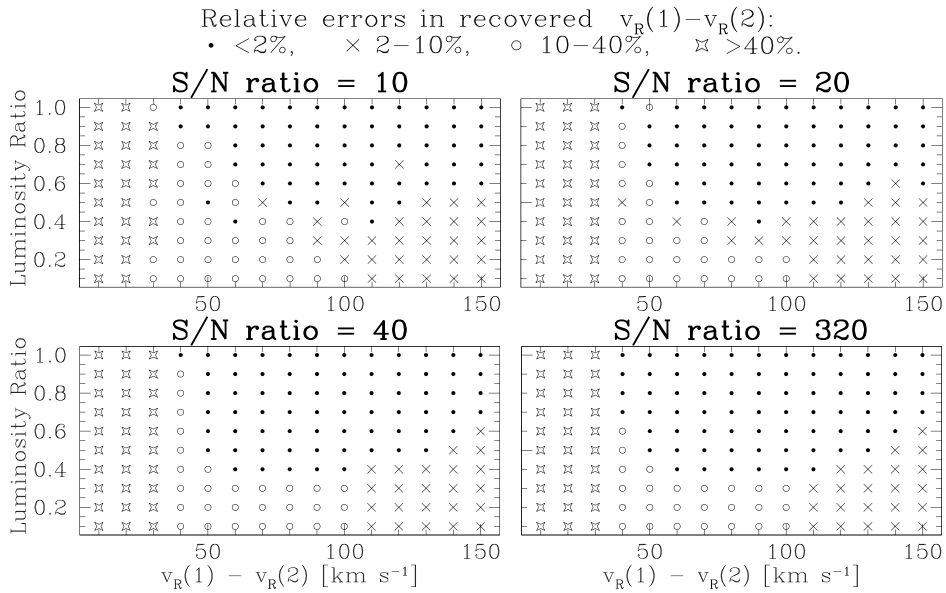

Figure 7. Results of Monte Carlo simulations to assess the recoverability of SB2 binaries in RAVE spectra. The difference between the true and recovered radial velocity difference of the two components is given for solar type SB2 and a range of ΔRV, S/N and luminosity ratio.

orbital solutions formally accurate to 1-2%. This is a fantastic number compared to ≤100 systems studied at similar accuracy by ground-based observations so far. These 16 000 stars will have their parallax measured to 5 micro-arcsec accuracy which corresponds to an error ≤0.5% in their distance if closer than 1 Kpc. Such extremely accurate parallaxes will be sed to directly constrain the values of several parameters (e.g. absolute luminosity) and physics used in orbital modeling, so that the atmospheric structure and global parameters of eclipsing binaries could be refined to *absolute* errors well below 1%.

3. RAVE and the SB2 binaries

RAVE (RAdial Velocity Experiment) is an ambitious program to conduct an all-sky survey (complete to V=15.5 mag) of radial velocities and metallicities of 50 million stars using the 1.2 m UK Schmidt Telescope of the Anglo-Australian Observatory (AAO), together with a northern counterpart, over the period 2006 – 2010. A key feature of the RAVE project is a pilot program aiming to observe 10^5 stars using the existing 6dF facility in unscheduled bright time over the period 2003–2005. This pilot program begun on April 11, 2003 and by the time this conference was held it logged the observations of 20 000 stars. The 6dF spectrograph brackets the CaII triplet region adopted for GAIA (c. Figure 2). Spectra are taken at a resolution of $R = 8000$.

The target list of the pilot program includes a large fraction of the 118 000 Hipparcos stars that are accessible from the southern hemisphere as well as some

of the 2 539 913 stars of the Tycho-2 catalog. The survey focuses on stars in the color range $0.4 < B - V < 0.8$. For these stars useful photometric parallaxes can be derived if meaningful trigonometric parallaxes are not available.

The RAVE main survey should utilize a new Echidna-style multi fiber spectrograph at the UK-Schmidt telescope and its northern counterpart. In the UK-Schmidt planned version it consists of a 2250-spine fiber array covering the full field of view (40 deg^2). The fiber positions are reconfigurable in ≈ 5 min. A detailed description of RAVE and in particular of its science goals, aiming to derive the kinematics and formation history of the Milky Way, can be found in Steinmetz (2003).

RAVE observes any given target star only once, even if with remarkable S/N. Therefore it is not possible to discover SB1 binaries or trace the motion of components in SB2 systems. However, the respectable resolution and high S/N of RAVE spectra allow it to detect all SB2 binaries with a suitable luminosity ratio and velocity separation at the time of the observation. Given the huge number of stars surveyed by RAVE, this would put useful statistical constraints (on velocity separation and luminosity ratio as a function of spectral type and metallicity) on the population of binary stars in the Milky Way. Figure 7 presents the results of simulations carried to out to infer the SB2 detectability by RAVE. They show that all F–M SB2 binaries with a luminosity ratio $\geq$0.5 and observed when velocity separation of their components is $\geq$35 km sec^{-1} will be recognized as such. And new SB2 binaries are already being discovered in the early data secured by RAVE in 2003!

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